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Simulation for assessing the liberalization of biofuels

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ABSTRACT

Global biofuel consumption has been growing in recent years as different countries worldwide have been exploring alternatives and complements to gasoline and diesel fuel for transport. This is due to a hike in oil prices and their increasing volatility as well as both a high dependence of the transport sector on oil and also because, arguably, the supply chain of biofuels emits less CO_2 than that of fossil fuels.

Biofuels have been available around the world for a while, with the aid of some government support. Brazil pioneered this renewable solution for transport, from the early 1930s, as the country had little access to local fuels, while oil and other alternatives became more expensive. Biofuels are currently widely considered as part of the solution to affordable fuels for transport. This paper makes use of a system dynamics model to analyse the current leading policies aiming at increasing the penetration of biofuels.

In this context, and given multiple uncertainties that include technology evolution and fuel prices, scenario analysis has been considered for the examination of different, extreme, though plausible, futures. Simulations, under extreme scenarios, helped in assessing the possibility of removing incentives (that is, leaving decisions to an open market) and a partial reduction of subsidies. This paper concludes that for the case of Colombia, the potential of biofuels seems promising.

Contents

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1. Introduction

Contemporary societies are confronting critical problems regarding high fuel prices, growing CO_2 emissions and climate variability. These are becoming more challenging, given the increasing energy needs around the world and the depletion of inexpensive non-renewable energy sources [1]. In this context, governments are considering energy alternatives, such as biofuels [2,3], as these are gradually becoming cost-competitive [4]. At the current state of development of the industry, biofuels still seem to need some support, given the structural barriers that were created by fuel suppliers over the last century [3].

However, as the main sources for the production of biofuels have been vegetable oils and sugars, and as the predominant crops are sugar cane, sugar beet, corn and oily seeds [3,5] and as these are also used to produced biofuels, the sector has been blamed for increases in food prices [3,6,7]. Though not the focus of this research, to take into account this serious concern, this paper considers biofuel feedstock that is being produced sustainably [8–10]. In particular, this paper considers feedstock for the production of biofuels in countries where the same crops may be used for human food but the use for biofuels does not compete with food production, as: (a) in some countries, land available (sometimes marginal) is capable of supporting important increases in biofuel production (see Section 3), (b) it is produced (and might expand its production further) in deserts or land that is inefficiently used for pasture, and (c) more R&D+I will bring further efficiency in food and biofuel production, and also in alternative feedstock for biofuel production.

It is important to note that this paper only examines first-generation biofuels. Fig. 1 shows the conversion process from feedstock to biofuels. While first generation biofuels are produced from feedstock that is also used as human food, such as soy beans, sugar cane and palm oil [5], second generation biofuels are produced from feedstock that is not used for human food but rather from sources such as agricultural and wood waste [11]. This article does not study second or third generation biofuels (coming from residues or microalgae) as the focus here is to assess how far the industry can progress under the current circumstances, without significant effect on human food stocks.

Ethanol and biodiesel can be used in conventional vehicles. Biodiesel has been used in pure and blended forms in conventional diesel vehicles. The blend between biodiesel and diesel is known as B# where the B indicates biodiesel and "#" indicates the biodiesel percentage in the blend (for example B10 means 10% of biodiesel and 90% of diesel). This is similar for ethanol; E20 is about the highest ethanol blend for conventional cars that does not harm regular motorcar engines and does not increase maintenance costs [2,5,12,13]. Table 1 shows some of the main advantages and disadvantages of ethanol and biodiesel.

Fig. 2 shows the evolution of world production of ethanol and biodiesel. This highlights that production is highly concentrated in a few countries. The leading producers are the US and Brazil for ethanol; and the EU, the US, Brazil and Argentina for biodiesel.

The introduction of flex-fuel vehicles has given consumers the possibility of choice between fuels (fossil and non-fossil), based on price differentials [13]. It has also provided governments with the possibility of creating new regulation for biofuel use. Note that the ethanol market has been liberalized in Sweden and Brazil [14–16].

These "flex-fuel" vehicles can use mixtures of ethanol and gasoline; they are designed for blends of 85% ethanol and 15% gasoline, i.e. E85 [5]. In Brazil, flex-fuel vehicles can use up to 100% of ethanol or E100 [12,17].

The Brazilian experience regarding ethanol production dates from the early 1930s [18]. In 1975, Brazil established government

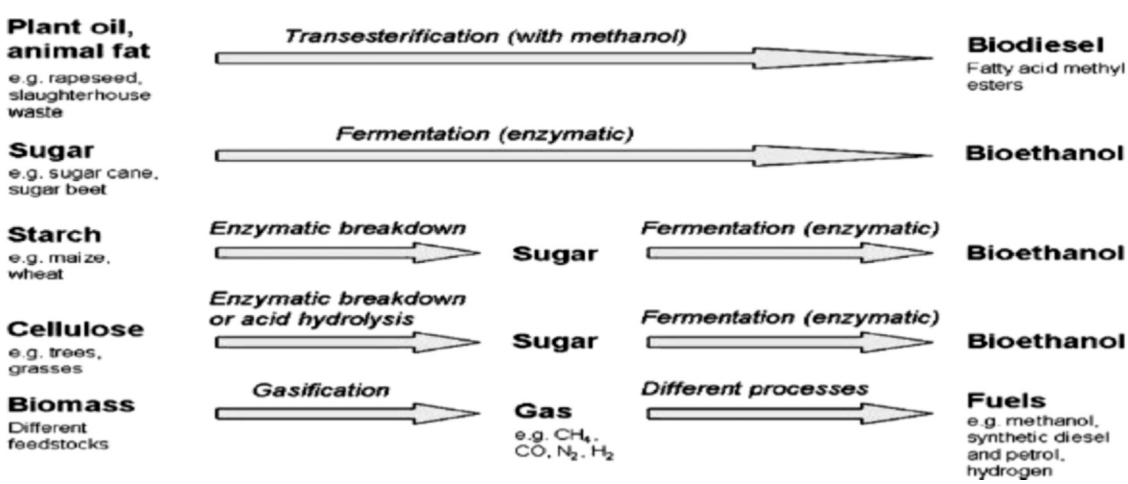

Fig. 1. Alternatives for fuel and biofuels production [5].

Table 1
Advantages and disadvantages of ethanol and biodiesel.

	Advantages	Disadvantages
Ethanol	Extends engine life, decreases CO_2 emissions and provides higher octane [9]	E100 delivers 70% of the mileage of gasoline (for the same volume of fuel), while E85 delivers 74% of the mileage [10]. Ethanol contains a lower caloric concentration than gasoline (while gasoline has a calorific value of approx. 32 kJ/l, ethanol has a lower caloric value, at approx. 22 kJ/l)
Biodiesel	Prolongs engine life, reduces need for maintenance and decreases CO_2 emissions. Also, efficient, clean, and better than diesel in terms of sulphur emission and biodegradability [5]	Blended biodiesel–diesel is vulnerable to fuel freezing, and reduces energy density [5]

subsidies for the ethanol industry under the Brazilian Proalcohol Program. As a consequence of this, ethanol started to replace a significant proportion of gasoline-use in the transport sector [16].

In 2003, the Brazilian government introduced flex-fuel vehicles (FFV). The country liberalized the ethanol market in 2005 and rapidly increased foreign participation in this sector. As a consequence of this, the cost of ethanol production decreased and ethanol production increased; Brazil became the largest ethanol exporter worldwide [19]. Fig. 3 shows the growing consumption of E100 in Brazil, between January 2005 and April 2009.

The focus of this paper is assessment of the liberalization of biofuels elsewhere. This requires consideration of particular issues regarding the agricultural and the refinery sectors involved, as well as policy aspects that need addressing. All these are country-specific and need to be examined before generalizations can be considered. This paper selected Colombia as a case for study because of its promising potential in this arena, as discussed in Section 3. In this broad context, modelling and simulation can support the analysis; in particular, the system dynamics (SD) approach seems a reasonable option as this has been used, over the years, in a number of similar environments [20]. Therefore, this paper addresses a number of questions, including: how sustainable is current policy in aiming at increasing the participation of biofuels in the mix with gasoline and diesel fuel? What is the effect of promoting free fuel-mix choice among consumers? Will it be convenient to liberalize the biofuels market, promoting imports and/or exports? What are the likely benefits of thorough biofuels liberalization?

Section 2 provides an overview of the SD literature on biofuels. Section 3 discusses the biofuels market in Colombia. In Section 4 we describe an SD model that has been built to study the dynamics of both the actual, and the potentially liberalized, biofuels market that might be developed in Colombia, following experiences of leading countries in this industry. Section 5 discusses simulation results and policy analysis. And finally, conclusions are given in Section 6.

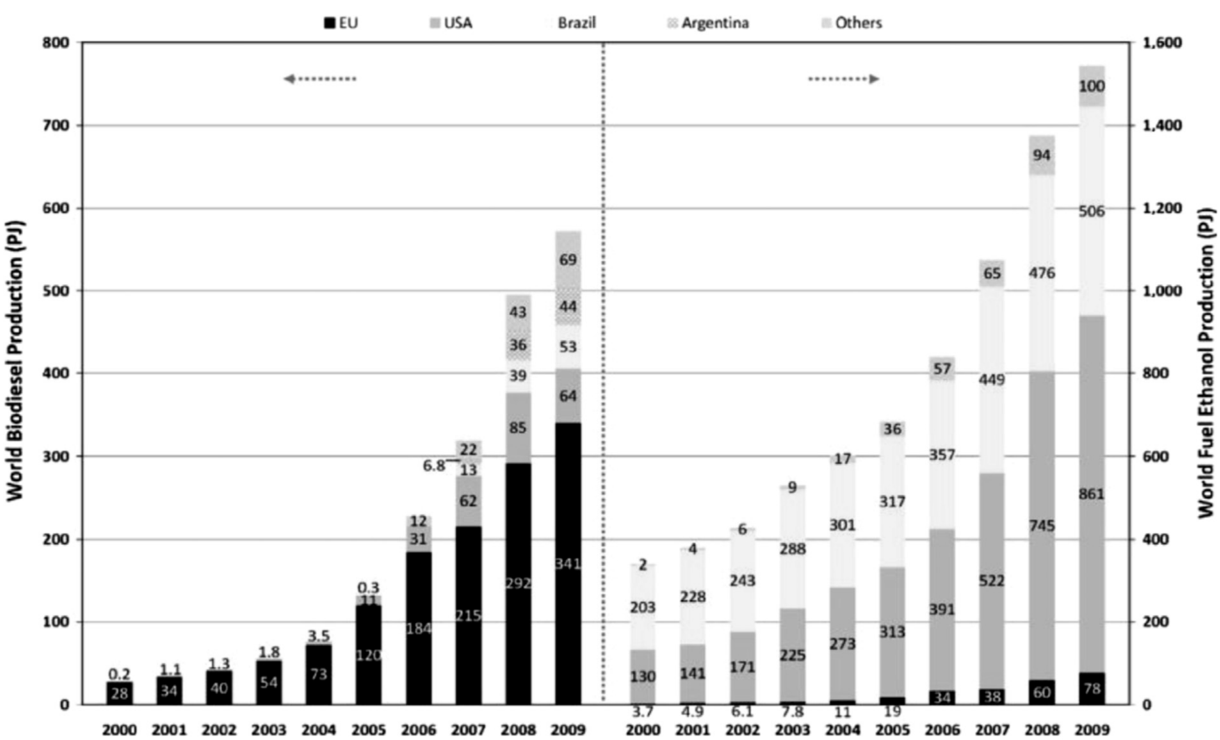

Fig. 2. Development of world biodiesel and ethanol production between 2000 and 2009 in PJ [16].

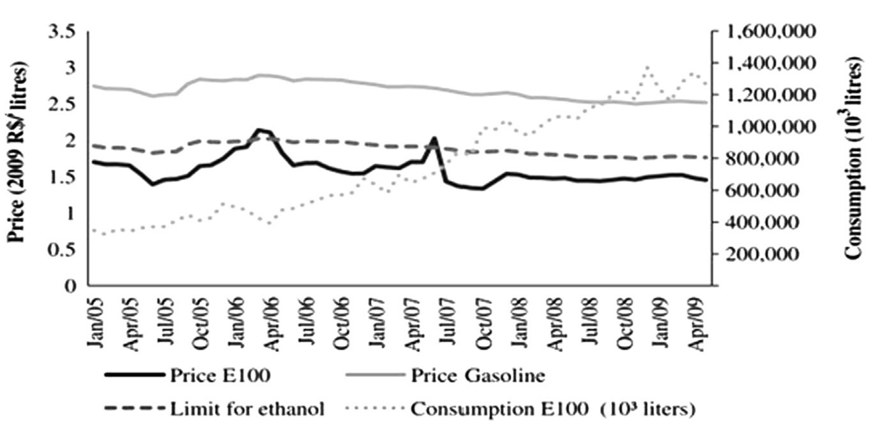

Fig. 3. Brazil E100 consumption and E100 price [14].

2. The system dynamics literature on biofuels

System dynamics (SD) – a simulation approach – has been used to investigate the biofuels industry. Bantz and Deaton report the impact of biodiesel production on the cost of soya [21], Musango et al. analyse the growth of biofuels production in South Africa [22], Florez and Franco discuss incentives for the biofuels market in Colombia [23], and Flynn and Ford assess the introduction of clean energy such as biomass and biofuels [24]. Pruyt and De Sitter developed a system dynamics model focused on food/bioenergy issues, to investigate the effects of the interactions between food production on bio-energy production worldwide [25]; Bush et al. evaluate the biodiesel transition in the US [26], and Vimmerstedt et al. developed a system dynamics model focused on the ethanol supply chain in the USA, and analyse incentives and R&D investment [27].

According to the authors' literature review, SD research has neither reported work regarding the effect of the liberalization of the biofuel industry on security of supply issues nor how this has been applied to liberalize the industry in a particular country – both of which are the aims of this paper. The next section discusses the biofuels market in Colombia.

3. The biofuels market in Colombia

Colombia has promising conditions for becoming a major biofuels producer as it has sufficient land available for this purpose (located in regions that marginally produce human food, and in deserts or unexploited regions) as well as adequate climatic conditions and lower labour costs than most other producers [28].

In Colombia, less than 1% of the potential agricultural land is used in farming sugar cane and palm oil. Note that by law, human food has a priority over exports and the production of biofuels. The potential of the best land for the production of sugar from sugar cane is seven times greater than the present capacity under production; furthermore, the potential of adequate (rather than the best) or of marginal land, for production of ethanol is 15 times greater than the actual area of land being used [28,29]. Similar numbers are observed in the case of feedstock coming from palm oil [29,30] – the potential is about ten times greater than the actual land area being used. These land areas do not include deserts that might be incorporated in farming alternative feedstock for manufacturing biofuels.

The biofuels industry in Colombia started in 2001 with the enactment of Law 693 [31]. With this legislation, the government establishes different incentives such as: tax exemptions, subsidies, mandatory blending for the production of ethanol from sugar cane as well as biodiesel from oil palm, and mandatory prices that ensure profitability for producers [32]. In 2010, the country started ethanol production from sour yucca [33] that traditionally has widely been used for non-human food.

Colombia produces biodiesel from palm oil, and ethanol from sugar cane or sour yucca [33,34]. Biofuels production in Colombia is shown in Table 2.

Colombia's biofuel production is still limited. Table 3 shows the ethanol and biodiesel production in different countries during 2012. However, given the land availability and weather conditions, Colombia could become a significant biofuels player, worldwide.

Colombia's production capacity has been following demand (depending on the goals set for the fuel mix) but does not significantly exceed demand, as a result of: (a) the current incentives in place, (b) the time that is needed to increase production levels [33,36] and (c) lack of further incentives to export.

However, the government has argued that, as the ethanol mandatory component of the mix will increase, ethanol production will not meet demand [33]. Fig. 4 shows current government mandatory supply and demand projections for ethanol. As can be observed, in the High probability of supply scenario, supply only exceeds demand projections up until about the year 2016; while in the Possible supply scenario (greater supply but less likely to occur), supply surpluses still only occur until the year 2019. In both cases, according to this government assessment, a deficit of ethanol will occur in the years to come. This paper assesses the soundness of these predictions. It also examines the effect of partially eliminating some of the current incentives and, finally, examines the effect of completely liberalizing the industry; that is, establishing legislation that allows consumers to choose fuel-blend, with prices fixed according to market conditions, the latter according to international fuel prices.

The liberalization of biofuels in Colombia should lead to greater production efficiency and cost reductions due to competition [18]. We developed a system dynamics model of the evolution of biofuel production to analyse the long-term effects of the liberalization of the biofuels market in Colombia. A model description is presented in the next section.

4. Model description

This section analyses the biofuels market in Colombia using a system dynamics model that incorporates key variables such as: investment in crops, refinery capacity, stocks of biofuels and fuels demand.

4.1. Dynamic hypothesis

Fig. 5 shows our dynamic hypothesis for a free biofuels market. This hypothesis establishes the synchronization that has to take place between ethanol manufacturing and feedstock production. On the one hand, demand for biofuels drives investment in new capacity when the margin between supply and demand falls short and when the business is profitable. On the other hand, additional land for feedstock production is acquired when this is needed and, simultaneously, when there is sufficient land available. In more detail, the feedback structure of the dynamic hypothesis indicates, as observed in Fig. 5 (Loop B1), that depending on the refining capacity, the effect of an increasing need for land will incentivize farming, and thus new land acquisition will be undertaken; after a lag, this will lead to increases in planting and feedstock production.

Table 2
Biofuels production in Colombia [33].

Biofuel	Production (L/day)	Feedstock
Ethanol	875,000[a]	Sugar cane and sour yucca
Biodiesel	1,967,904	African palm oil

[a] 25,000 L/day of sugar cane are produced from sour yucca.

Table 3
Ethanol and biodiesel production by country in thousand millions of litres in 2012 [35,36].

Country	Ethanol	Country	Biodiesel
United States	**50345.9**	**United States**	2747.52
Brazil	**21035.53**	**Canada**	114.48
Europe Union	**4311.584**	**Germany**	2804.76
Canada	**1699.65**	**China**	515.16
China	**2100.904**	**Brazil**	1488.24
Colombia	**368.447**	**Colombia**	171.72
		Others	7841.88

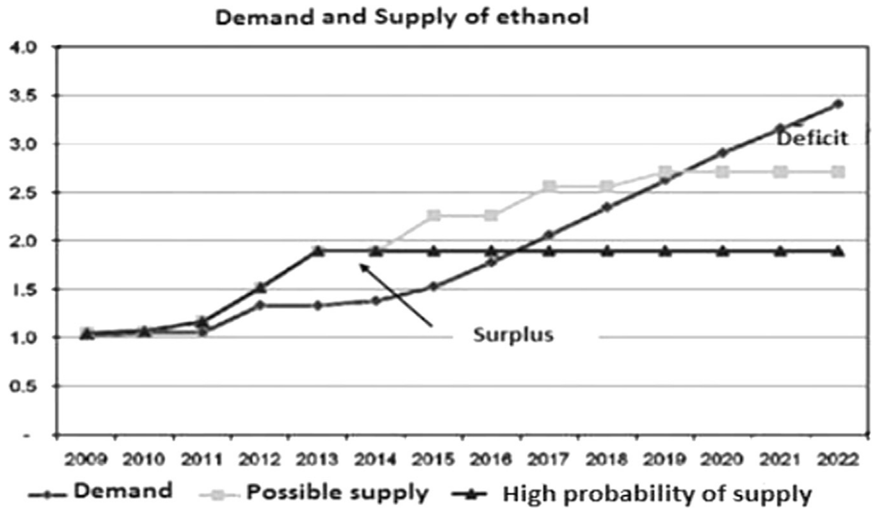

Fig. 4. Ethanol supply vs. ethanol demand in Colombia [37].

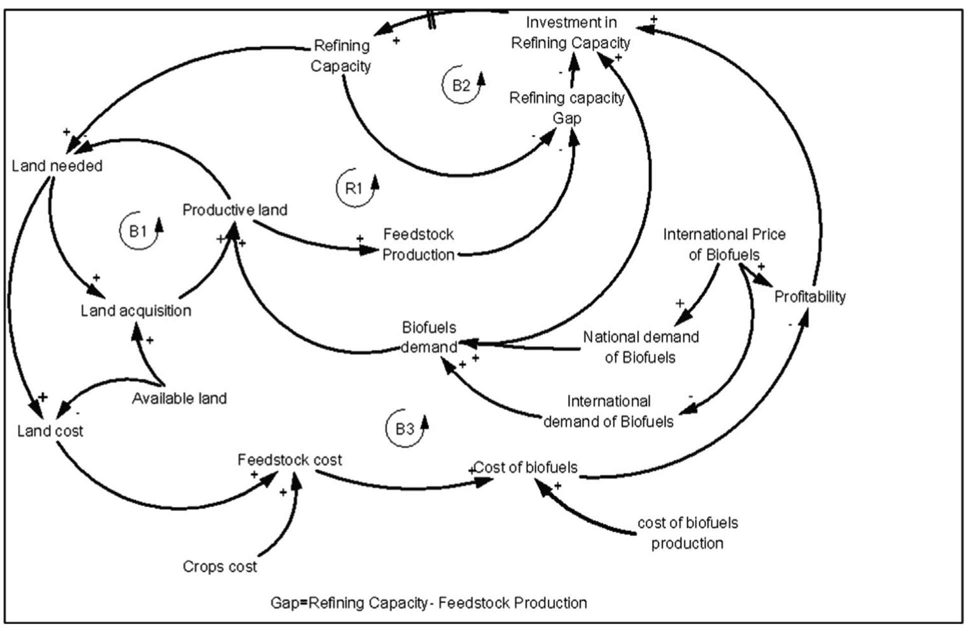

Fig. 5. Dynamic hypothesis for biofuels under market liberalization in Colombia.

Refining capacity and feedstock production, together, determine refining capacity gap (i.e. refining capacity needs). By increasing investment, new refining capacity will be built and, consequently, increasing land needed to satisfy demand for feedstock, increasing planting and feedstock production. These describe the investment-refining loop, and the refining-capacity gap loop (B2, R1 respectively).

Land needed depends on refining capacity. As more land is acquired for this purpose, land cost increases, which affects the feedstock cost and biofuels costs. If cost of biofuels is high, profitability is low, affecting investment in new refining capacity. If investment in new refining capacity increases, larger refining capacity will be in place (loop B3).

4.2. Stocks and flows diagram

To analyse market dynamics we develop a stocks and flows diagram to properly build a simulation model. This was undertaken for the purpose of assessing biofuels policy, particularly regarding market sustainability under current circumstances and also considering market liberalization. These we assess through the evolution of the supply chain variables of the industry, including: feedstock production, refining capacity and demand for ethanol and biodiesel (this, under different market conditions). Following the dynamic hypothesis, the stocks and flows diagram (Fig. 6) shows the coupling between manufacturing of biofuels and feedstock production. As previously indicated in the dynamic hypothesis; on the one hand, new capacity will be built depending on the refining capacity gap (margin) and the profitability of the business. On the other hand, additional land will be acquired for feedstock production depending on land requirements and land availability.

Capacity investment depends on profitability. After deciding investment in each period, the new refining capacity will be available on average four years later, which is the time that has been stipulated for plant construction, with a plant-life of 25 years [38,39]. Biofuel demand was modelled according to a logit model that depends on fuel price and performance.

4.3. Model equations and assumptions

Refinery capacity depends on capacity under construction and refinery reduction

$$\frac{dR}{dt} = CAR - RC \tag{1}$$

R represents refinery capacity, CAR capacity acquisition rate and RCD refining capacity depreciation.

Crop capacity depends on farming and harvesting. Feedstock production depends on agricultural production and refining requirements

$$FSP = \mathrm{Min}(AP, R, BD) \tag{2}$$

where FSP represents feedstock production, AP agricultural production, R refining capacity and BD biofuel demand.

Biofuels demand was modelled according to logit model

$$BD = \frac{\frac{BP}{BPP}^{\gamma}}{\left(\frac{BP}{BPP}^{\gamma}\right) + \left(\frac{FP}{FPP}^{\gamma}\right)} \tag{3}$$

where BD represents the percentage of biofuel with respect to the total, BP biofuel price, BPP biofuel performance, FP fossil-fuel price; FPP fossil-fuel performance; and γ is a parameter [40].

The model was calibrated using the E85 demand data for Sweden [14].

Investment in refinery capacity is undertaken if this is required, and long-term returns are positive. Annex 1 includes a synthesis of the above equations and other relevant ones, as well as further explanation of equations and major assumptions. The next section discusses simulation results for the effect of different scenarios for liberalizing the biofuels market in Colombia. We use a time horizon of 18 years, from 2013 to 2030; this horizon is long enough to assess the dynamics of the biofuel industries.

5. Results

At the present time, the biofuels market in Colombia is regulated by government [31]. Government regulates fossil fuels as well as the biofuels blends and the price of biofuels. Four scenarios are being considered in order to analyse the possible evolution of the actual market, as shown in Fig. 7.

Liberalized market. Price and blend percentage are not regulated, blend mix varies endogenously in the model. Price depends on the international price of biofuels and the blend depends on the relationship between the fossil-fuel price and the biofuel price.

Free price and regulated blend market. Blend is an exogenous variable and biofuels' prices depend on international price.

Highly regulated market. The price and blend percentage (biofuels and fossil fuels) are imposed by government (exogenous variables). This scenario is the base-case scenario.

Free blend and regulated price. The blend (biofuel and fossil fuel) is an endogenous variable and the blend percentage is based on the relation between fossil fuel and biofuel prices. Biofuels' prices are exogenous. Regulated biofuel prices are higher than the fossil fuel price.

The paper only analyses two extreme scenarios: one, under the present conditions and the other one under conditions of complete liberalization. The other two intermediate scenarios, which add little to policy analysis, are not discussed in the paper. However, two more scenarios are incorporated in the analysis to take into account the effect that external markets may have on the two chosen ones, regarding international prices and the possibility of imports and exports.

The results from the analysed scenarios are presented in the next sections.

5.1. Base-case scenario: highly regulated market

This scenario represents the current state of the ethanol and biodiesel market, where biodiesel and ethanol prices are regulated

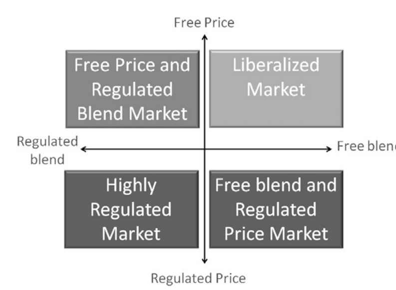

Fig. 7. Scenarios for analysing biofuels markets.

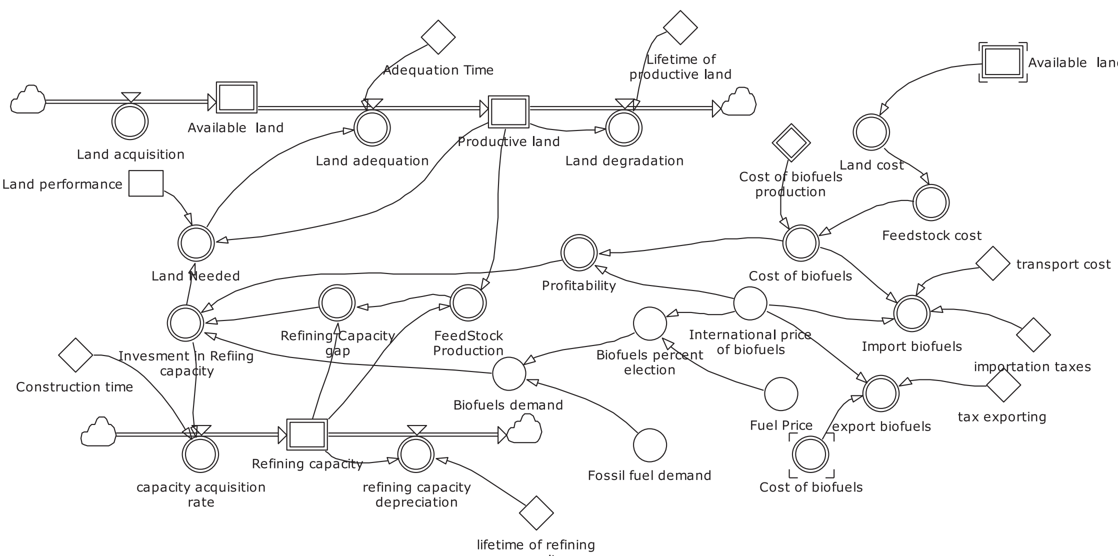

Fig. 6. Stocks and flows diagram of biofuel production under market liberalization in Colombia.

and government ensures the profitability of investors. Blends are currently E10 for ethanol and B10 for Biodiesel.

5.1.1. Base-case scenario: without external market (scenario 1)

Figs. 8 and 9 show simulations of demand and production capacity, for both ethanol and biodiesel. In both cases, it can be observed that biofuels production meets demand within the initial years of the simulation; once production capacity reaches demand, production closely follows.

These results are explained by the dynamic hypothesis (see Fig. 5), which establishes that as long as the conditions are favourable (demand, biofuel prices and land availability) then more biofuel production-capacity is constructed and more land is incorporated for the required feedstock production. Once production capacity overtakes demand, production capacity oscillates because of old plant retirement and the time that it takes for both the construction of new capacity and for the production of larger quantities of feedstock.

The current market guarantees high profitability and stability to investors. Under these conditions, biofuels growth will be low, missing the opportunities provided by Colombia's great natural potential, as discussed previously.

5.1.2. Base-case scenario: with external market (scenario 2)

Figs. 10 and 11 show simulations of demand and production capacity for both ethanol and biodiesel. The ethanol market shows imports at the beginning of the simulation and then ethanol production capacity meets demand within the early years of the simulation; once this stage is reached, production closely follows demand. The biodiesel market at the beginning shows production below demand but then production capacity exceeds demand and biodiesel surpluses are exported.

In these cases, the causality in Fig. 5 explains why imports take place to meet demand, only while new capacity is being built. For ethanol, when production capacity exceeds demand, no further imports take place because national prices are competitive but not competitive enough to promote exports, as they would not compensate transport costs. For biodiesel, when production exceeds demand, capacity keeps increasing to meet external demand as national prices are more competitive than international prices.

5.2. Liberalized market

In this scenario, blend and price are not regulated by government, and some consumers choose between gasoline and E85; others choose between diesel and B100 (this is represented using a logit equation).

5.2.1. Liberalized market: without external market (scenario 3)

Fig. 12 shows simulations of ethanol demand and ethanol capacity production. In this case, production meets demand after a fairly long period of simulation. This is because ethanol demand is higher than the regulated market can supply, and profitability is lower.

Fig. 13 presents simulations of biodiesel demand and biodiesel production. In this case, biodiesel production closely follows demand.

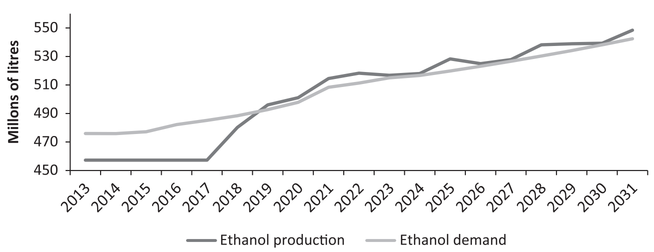

Fig. 8. Ethanol demand and ethanol production, base scenario.

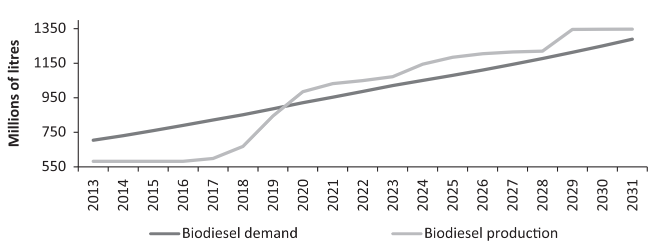

Fig. 9. Biodiesel demand and biodiesel production, base scenario.

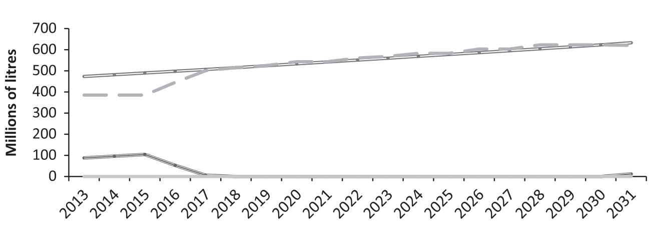

Fig. 10. Ethanol demand, production, imports and exports, all over 2013–2031, scenario 2.

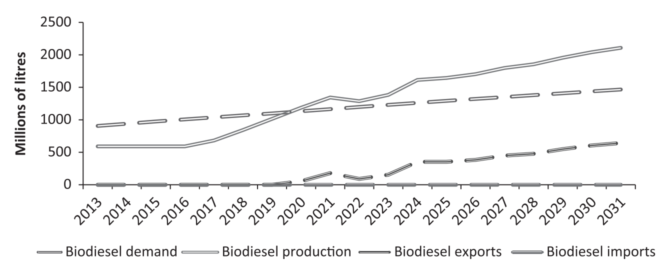

Fig. 11. Biodiesel demand, production, imports and exports, all over 2013–2031, scenario 2.

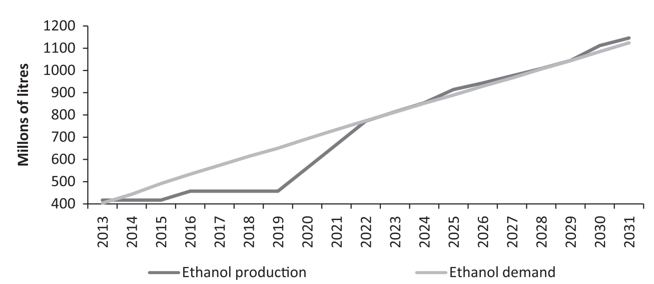

Fig. 12. Ethanol demand and ethanol production under a liberalized market scenario.

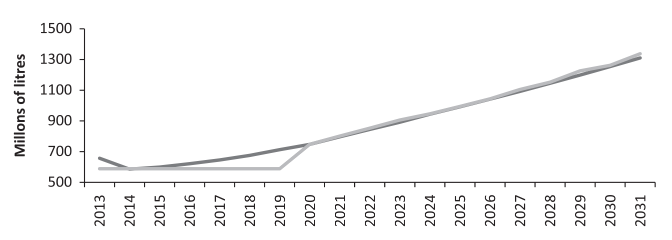

Fig. 13. Biodiesel demand and biodiesel production, scenario 3.

5.2.2. Liberalized market: with external market (scenario 4)

Fig. 14 shows simulations of demand, imports, production and exports of ethanol. In this case, production meets demand at the beginning of the simulation. Simulation shows that during the initial years, ethanol imports take place when production is lower than demand; when ethanol production meets demand, ethanol imports are negligible as national production is cheaper than imports.

Fig. 15 shows simulations of demand, imports, production and exports of biodiesel. In this case, production meets demand over most of the simulation period. In this scenario it is possible to observe biodiesel exports during the whole simulation period. This is because international prices are higher than local prices, which represents an opportunity to expand biodiesel production.

5.3. Comparison between scenarios

Fig. 16 presents simulations of ethanol price for the abovementioned scenarios: E10 and E85, for regulated and liberalized markets, respectively. We observe that E85 prices are lower than E10 prices (i.e. that under a liberalized market, E85 attains lower prices than E10).

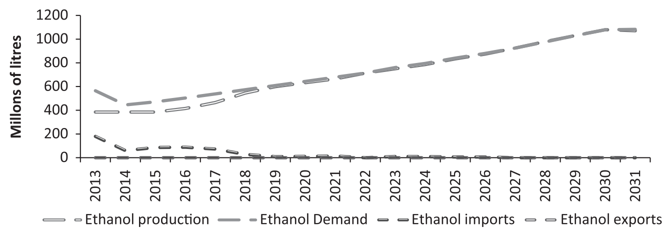

Fig. 14. Ethanol demand, production, imports and exports, scenario 4.

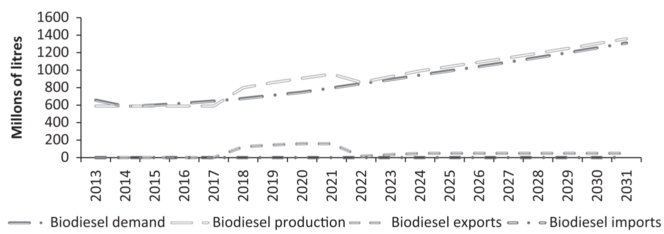

Fig. 15. Biodiesel demand, production, imports and exports, scenario 4.

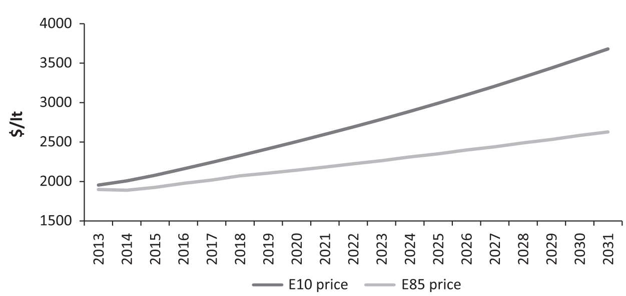

Fig. 16. Ethanol price under different scenarios.

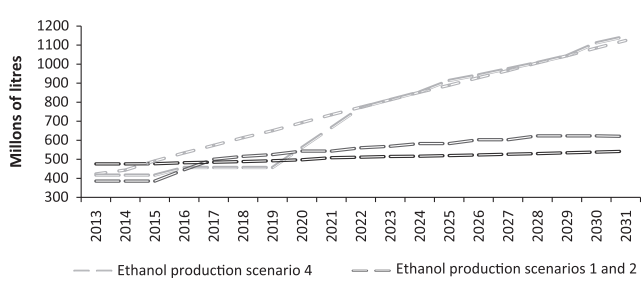

Fig. 17. Ethanol production and demand under different scenarios.

Fig. 17 presents simulations of ethanol production for the four scenarios being considered in this paper. Results show that under the liberalized scenario without external markets, ethanol reaches its highest production level. This is due to the fact that ethanol price is lower than gasoline price and that ethanol production in a liberalized market grows to meet demand (at a higher level of ethanol concentration).

Fig. 18 presents simulations of biodiesel prices for the B10 and B100 scenarios, for the regulated and liberalized market, respectively. It can be observed that B100 prices are higher than B10 prices across the simulation period.

Fig. 19 presents production comparisons between the four scenarios. Results show that under a regulated market, biodiesel production is low as there are no exports; and that under a liberalized market with import/export, biodiesel attains its highest production, as demand is higher when the market is liberalized and exports take place. When exports are possible, production exceeds demand, given the opportunities of lower local costs, compared with international prices. Production oscillations are explained by the time it takes to build new capacity. Note that there are lags between investment opportunities and getting new capacity in place. This is also the case with ethanol production although less pronounced given that it depends more on imports.

Comparison between scenarios suggests the needed in both cases – ethanol and biodiesel – of R&D investment in biofuels in Colombia; this, with the purpose of increasing productivity and reducing prices, making the industry more competitive worldwide.

5.3.1. CO_2 scenarios

Fig. 20 presents comparisons of CO_2 emission between free and regulated scenarios. It can be observed that the free-market scenario attains lower emissions due to increases in biofuels consumption – around 30% less emissions. As expected, high blends of biofuels emit lower emissions than low blends, which constitutes a further incentive to liberalizing biofuels [5].

Emissions are referred to the life cycle of biofuels in Colombia, resulting in the replacement of gasoline and biodiesel by ethanol

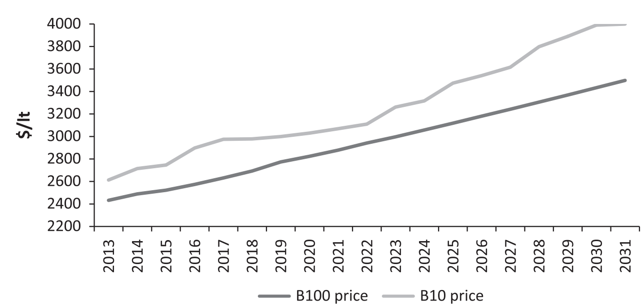

Fig. 18. Biodiesel price under different scenarios.

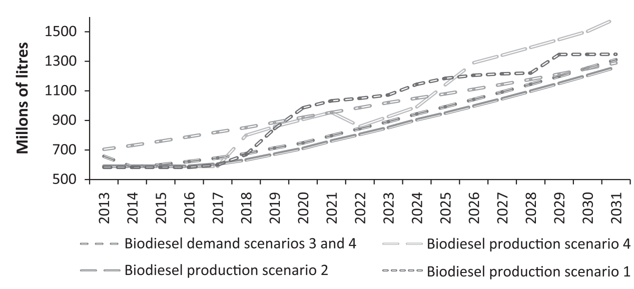

Fig. 19. Biodiesel production and demand under different scenarios.

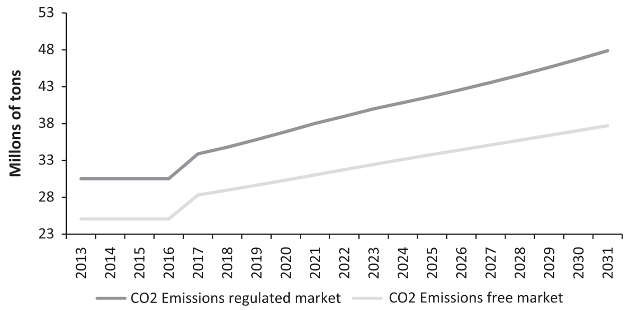

Fig. 20. CO_2 emissions: free markets and regulated markets.

and diesel, respectively – the corresponding reductions are of the order of 74% and 83% CO_2 savings per litre [30].

6. Conclusions

This paper provides insights into the potentials of the biofuels industry. It examines the likely benefits of: (a) encouraging a higher component of biofuels in the fossil mix and, and (b) the cross border liberalization of the market, facilitating import and exports of biofuels. This is illustrated by the Colombian case.

As indicated in the text, the biofuels market in Colombia, under current conditions, limits the business activity of investors, as regulation does not significantly stimulate a higher biofuel mix and exports. However, this paper shows that the potential is significant and that a more vigorous industry is feasible, as: (a) there is from 7 to 15 times more land available, in part for the production of biofuels, (b) the economics of the biofuels industry in that region of the world is encouraging (simulations indicate that the expansion of the industry takes place under both scenarios), and (c) with more I&D+I alternative feedstock might be viable. Furthermore, there is sufficient land for both farming human food and sustainable production of biofuels.

Liberalization seems to be a promising option for ethanol and biodiesel, as demand, under a liberalized market, may largely exceed regulated demand. The external market seems a favourable option for the Colombian biodiesel market, given the positive cost differentials and the Colombian agricultural potential. With respect to ethanol, the external market seems a good option for imports, in terms of price, in the case that arid land becomes insufficient and inefficient for biofuel production.

Note that the production of ethanol from sugar cane does not compete with that of sugar as the potential land is up to 15 times greater than the land actually in use. Further, it has been established by law that food is a priority over ethanol production and exports. And, as indicated in Table 2, some ethanol production already comes from sour yucca, which is not used for human food and is produced in marginal land or deserts – this will be more profitable with the support of some R&D+I [29,41].

Although sugar cane is the most efficient feedstock for first-generation ethanol in Colombia – and Colombian land is the most fertile for sugar cane applied to ethanol production, worldwide – accessible land is limited. The need to use some of the land for other crops has the effect of reducing Colombian ethanol competitiveness internationally. R&D should help to overcome this problem.

From this perspective, and also from an environmental point of view, Colombia might need to invest in R&D, applied to the biofuels industry, in order to reduce costs, and aim at a faster rate of agro-industrial growth, providing opportunities matching its natural potential and the export sector. Results indicate that under the scenarios considered, CO_2 emissions from ground transportation might be reduced substantially, for the most polluting sector in Colombia (in that part of the world, transport emits much more CO_2 than power generation as almost 80% of electricity derives from hydroelectricity).

The model helps to understand possible system behaviours and also to identify key factors that should be considered. For ethanol and biodiesel, the liberalization scenario shows that there are favourable conditions for a liberalized market.

The paper succeeds in its purpose on at least two counts: it shows the likely benefits and sustainability of biofuels when feedstock is based on crops that are produced in marginal lands; and, it also shows the potential benefit of thorough liberalization of biofuels. Generalizations of this experiment to other countries seem promising if major factors are considered: land used that is not required for food production, weather conditions that are appropriate for the selected crops and the availability of sufficient incentives for industry. Further, a more in-depth analysis would probably provide avenues for extensive use of second and third generation biofuels.

Annex 1

Equations, explanations and assumptions	Units
$\frac{dR}{dt} = \mathrm{CAR} - \mathrm{RCD}$	L/yr
Refining capacity increases according to investment in new capacity (CAR) and decreases depending on obsolescence (RCD)	
$\mathrm{FSP} = \mathrm{Min}(\mathrm{AP}, R, D)$	tons/yr
Crop capacity depends on farming and harvesting. Feedstock production – Eq. (2) – depends on agricultural production and refining requirements.	
$\mathrm{BD} = \frac{\frac{\mathrm{BP}^{\gamma}}{\mathrm{BPP}}}{\left(\frac{\mathrm{BP}^{\gamma}}{\mathrm{BPP}}\right) + \left(\frac{\mathrm{FP}^{\gamma}}{\mathrm{FPP}}\right)}$	%biofuels election
BD represents the percentage of biofuel with respect to the total, BP biofuel price, BPP biofuel performance, FP fossil-fuel price; FPP fossil-fuel performance; and γ is a parameter [33]. The model was calibrated using the E85 demand data for Sweden.	
$R_i = \frac{V_i}{tc}$	vehicles/year
R_i represents the number of withdrawn vehicles, (V_i) the number of circulating vehicles at any time, and (tc) the lifespan of vehicles. Vehicle fleet increases at a rate of 6.6% per year – though high, this is useful to test the potential of the biofuel industry.	
$\mathrm{IPR}(t) = \begin{cases} 0 & 0 < \mathrm{RE}(t) < 0.05 \\ k & 0.05 < \mathrm{RE}(t) < 20 \\ N & 0.7 < \mathrm{RE}(t) < 1 \end{cases}$	L/yr
Investment in new refineries (IPR) depends on its expected profitability (RE). This assumes that investors will build larger facilities depending on the returns on investment. This was calibrated.	

The model used adaptations of data from Sweden, assuming rational behaviour of consumers – in terms of price.

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